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Light Water Reactor Sustainability Program

Development Plan for the External Hazards Experimental Group

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Curtis L. Smith
Douglas Burns
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March 2016

DOE Office of Nuclear Energy

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ABSTRACT

This report describes the development plan for a new multi-partner External Hazards Experimental Group (EHEG) coordinated by the Idaho National Laboratory (INL) within the Risk-Informed Safety Margin Characterization (RISMC) technical pathway of the Light Water Reactor Sustainability Program.

The RISMC pathway is developing a suite of new tools and methods for advanced evaluation of facility risk. The RISMC "Toolkit" currently includes a suite of tools, methods, and data focused on evaluation of risk from external hazards (e.g., seismic and flooding events), which have been shown to be dominant risk contributors in probabilistic risk assessments performed for operating nuclear power plants (NPPs). The external events activity (EEA) within the RISMC pathway is tasked with developing new advanced tools and methods focused on evaluation of multi-hazard external risk to NPPs (e.g., combined seismic and flooding primary and secondary events). The EHEG will provide technical expertise and experimental small- and large-scale testing data needed for development and validation of tools and methods in the RISMC toolkit for external hazard safety evaluations.

The EEA within RISMC has two key elements: (1) an organizational and research framework provided by INL and (2) a coordinated group of university and national laboratory partners with the complementary expertise and experimental capabilities needed to conduct small- and large-scale external hazard-focused experiments. This cooperative group, known as the EHEG, will allow INL to leverage a range of existing capabilities to meet the unique needs of RISMC tool and method development. In addition, the capabilities of the EHEG could be used to address needs of other national laboratories.

Currently, there is limited data available for development and validation of the tools and methods being developed in the RISMC EEA. The EHEG is being developed to obtain high quality, small- and large-scale experimental data for validation of RISMC tools and methods in a timely and cost-effective way. The group of universities and national laboratories that will eventually form the EHEG (which is ultimately expected to include both the initial participants and other universities and national laboratories that have been identified) have the expertise and experimental capabilities needed to both obtain and compile existing data archives and perform additional seismic and flooding experiments. The data developed by the EHEG will be stored in databases for use within RISMC and made available through the INL Seismic Research Group website[1],as appropriate. These databases will be used to validate the advanced external hazard tools and methods.

The EHEG will include recognized experts in the fields of seismic and flooding hazard assessment. These experts will initially be drawn from INL, the University of Buffalo, Purdue University, University of Illinois, North Carolina State University, Idaho State University, and George Washington University. A detailed table of the capabilities of each EHEG partner is provided in Appendix A.

There are several near term tests already planned and actively underway to gather data to validate both seismic and flooding models. These are briefly discussed in Section 4 of this report.

[1] The INL Seismic Research Group website is located at https://seismic-research.inl.gov/SitePages/Home.aspx

ACKNOWLEDGEMENTS

The Light Water Reactor Sustainability (LWRS) Program at INL commissioned this report. Input on the intellectual and physical capabilities of the external hazards experimental group was provided by each of the six founding university partners: University at Buffalo, Purdue University, The George Washington University, North Carolina State University, University of Illinois, and Idaho State University. Additionally, Professor Chad Pope, Alison Wells, and David Kamerman from Idaho State University contributed to Section 4.2.

CONTENTS

FIGURES

ACRONYMS

DOE	Department of Energy
EEA	external events activity
EHEG	External Hazards Experimental Group
EPRI	Electric Power Research Institute
INL	Idaho National Laboratory
LWRS	Light Water Reactor Sustainability
MOOSE	Multiphysics Object Oriented Simulation Environment
NLSSI	non-linear soil-structure-interaction
NPP(s)	nuclear power plant(s)
PRA(s)	probabilistic risk assessment(s)
R&D	research and development
RIMM	risk-informed margins management
RISMC	Risk-Informed Safety Margin Characterization
SPRA	seismic probabilistic risk assessment
SSCs	structures, systems, and components
SSI	soil-structure-interaction

Development Plan for the External Hazards Experimental Group

1. INTRODUCTION

This report describes the development plan for a new multi-partner External Hazards Experimental Group (EHEG) coordinated by the Idaho National Laboratory (INL) within the Risk-Informed Safety Margin Characterization (RISMC) technical pathway of the Light Water Reactor Sustainability (LWRS) Program (Smith et al. 2015). As described in more detail later in the report, the RISMC pathway is developing a suite of new tools and methods for advanced evaluation of facility risk. The RISMC "Toolkit" currently includes a suite of tools, methods, and data focused on evaluation of risk from external hazards (e.g., seismic and flooding events), which have been shown to be dominant risk contributors in probabilistic risk assessments performed for operating nuclear power plants (NPPs). The external events activity (EEA) within the RISMC pathway is tasked with developing new advanced tools, methods, and data focused on evaluation of multi-hazard external risk to NPPs (e.g., combined seismic and flooding primary and secondary events). The EHEG will provide technical expertise and experimental small- and large-scale testing data needed for development and validation of tools and methods in the RISMC toolkit for external hazard safety evaluations.

1.1 Overview of the External Hazards Experimental Group

The EEA within the RISMC pathway has two key elements: (1) an organizational and research framework provided by INL and (2) a coordinated group of university and national laboratory partners with the complementary expertise and physical capabilities needed to conduct small- and large-scale external hazard-focused experiments. The coordinated group in the second element (i.e., the EHEG) will allow INL to leverage a range of existing capabilities to meet the unique needs of the EEA and RISMC toolkit development. In addition, the capabilities of the EHEG could be used to address needs of other national laboratories. The initial partners in the EHEG are identified in Figure 1, below.

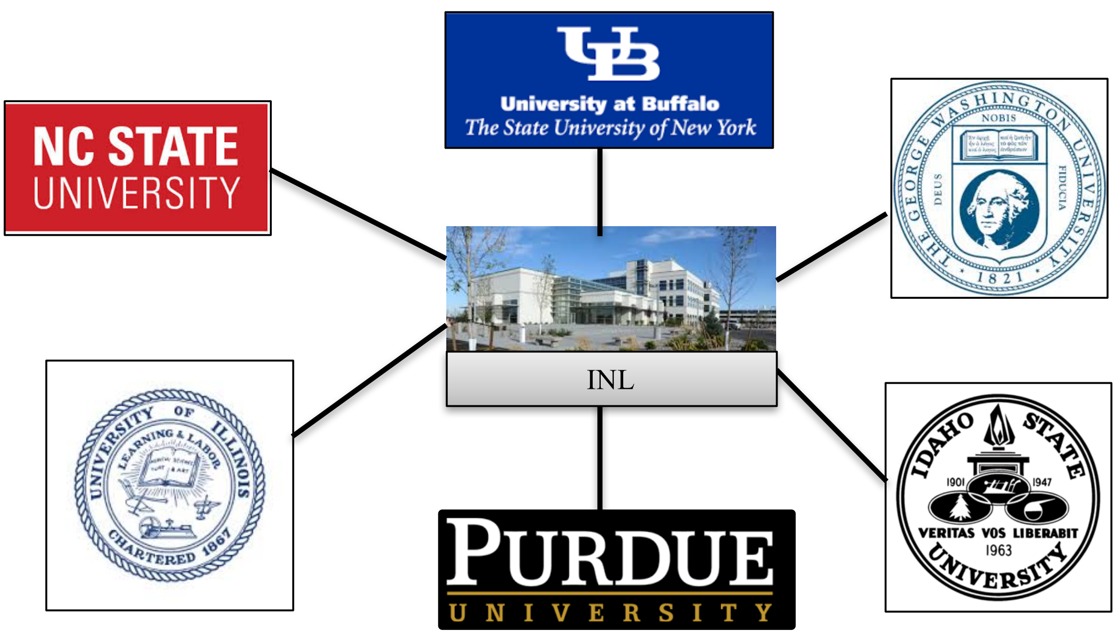

Figure 1. Initial External Hazards Experimental Group partners

1.2 Outline of this Report

Section 2 of this report provides additional information on the RISMC pathway and LWRS program. Section 2 also describes in more detail the verification and validation needs of the RISMIC Toolkit and the role of the EHEG within the existing activities. Section 3 describes the EHEG intellectual and physical testing capabilities and the structure and organization of the EHEG. Section 4 describes near-term small- and large-scale testing activities currently ongoing or under development. Section 5 provides a summary of the report. Appendix A to this report provides additional tables detailing the intellectual and physical testing capabilities of the EHEG.

2. ROLE OF THE EXTERNAL HAZARDS EXPERIMENTAL GROUP WITHIN THE LIGHT WATER REACTOR SUSTAINABILITY PROGRAM

2.1 Background on the Light Water Reactor Sustainability Program

In its 2010 Nuclear Energy Research and Development Roadmap: Report to Congress (DOE 2010), the United States Department of Energy (DOE) describes Research and Development (R&D) Objective 1 as, "develop technologies and other solutions that can improve the reliability, sustain the safety, and extend the life of the current reactors." The LWRS program is the primary programmatic activity to address this stated objective (for more information, see INL/EXT-11-23452 (INL 2015)).

Within the LWRS, there are four R&D pathways that address Objective 1. These pathways are:

(1) Materials Aging and Degradation

(2) Risk-Informed Safety Margin Characterization

(3) Advanced Instrumentation, Information, and Control Systems Technologies

(4) Reactor Safety Technologies

Activities associated with the EHEG will sit within Pathway 2, RISMC.

2.2 Background on the Risk-Informed Safety Margin Characterization Pathway

A systematic approach to the characterization and assessment of safety margins, and the subsequent margins management, represent vital inputs to licensee and regulatory analysis and decision-making. The purpose of the RISMC technical R&D pathway is to develop tools, methods, and data that support plant decisions using risk-informed margins management (RIMM) strategies. The aim of RISMC is to improve the economics of aging management while ensuring the reliability and safety of operating nuclear power plants over periods of extended plant operations.

The goals of the RISMC R&D Pathway are twofold:

(1) Develop and demonstrate a risk-assessment method that is coupled to safety margin quantification that can be used by NPP decision makers as part of RIMM strategies.

(2) Create an advanced RISMC Toolkit that enables more accurate representation of NPP safety margins.

The EHEG directly supports goal (2), above, and indirectly supports goal (1) by providing experimental data for the verification of tools within the RISMC Toolkit. The RISMC Toolkit is being built using INL's Multiphysics Object Oriented Simulation Environment (MOOSE) High Performance Computing framework (Gaston et al. 2009). MOOSE is INL's development and runtime environment for the solution of multiphysics systems that involve multiple physics-based models or multiple simultaneous physical phenomena. Models built within the MOOSE framework can be coupled, as needed, for assessing a particular real-world problem or scenario, including the assessment of facility performance when impacted by external hazard phenomena (e.g., seismic or flooding events).

The advanced methods and tools in the RISMC toolkit can be used within a RIMM approach to improve decision making by providing a technical basis to assess and analyze both the breadth of real world external hazard scenarios (Figure 2) and the potential impact of the hazard effects on the NPP. Importantly, external hazards of interest have a primary impact on the nuclear facility; but, as shown in Figure 2, these primary phenomena may also lead to secondary effects, which have not been robustly assessed in past practice. Examples of primary impacts of external hazards are seismic shaking, flooding, and high winds. Examples of secondary effects induced by seismic and/or flood events are dam and levy failure, landslide, internal flood, and internal fire. The correlation and temporal relationship of these primary and secondary hazards complicate the determination of safety in any complex facility.

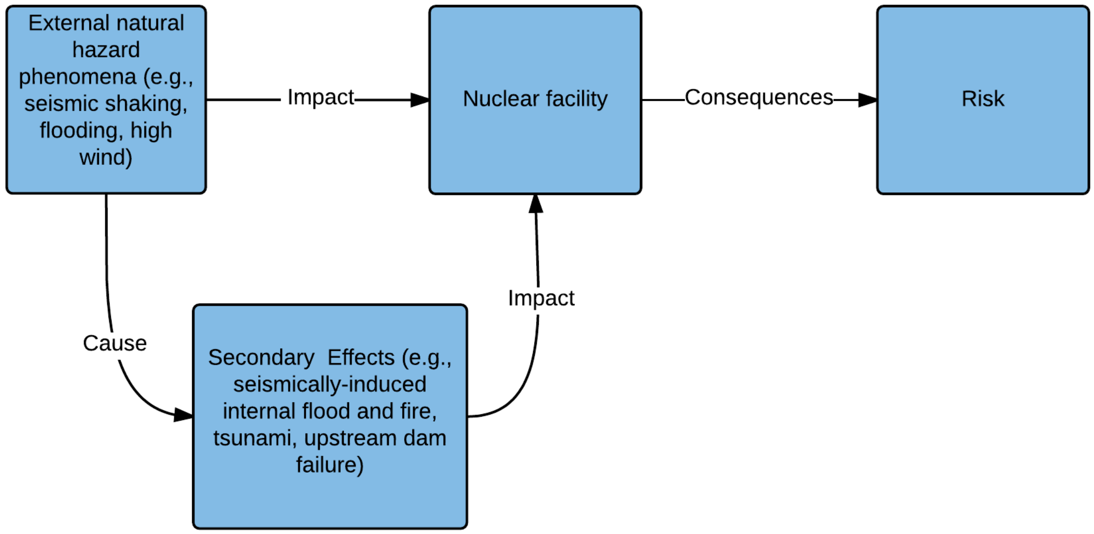

Figure 2. Potential primary and secondary external hazard propagation at NPPs

An example of a scenario that RISMC is uniquely capable of assessing and analyzing is presented in Figure 3. This scenario includes a seismic event that may lead to failure of a flood protection levee, as in addition to, the safety-related structures, systems and components (SSCs) of the NPP. The scenario in Figure 3 involves a primary hazard (seismic shaking) and secondary effects. The secondary effects may include both flooding (internal and external) and thermal-hydraulic-related effects (resulting from the flooding) that may lead to an impact to the reactor core.

A similar scenario, in which the RIMM approach will be applied at a generic NPP with a flood protection levy and a defined seismic hazard, will be used as a demonstration problem. The analysis will be initiated with potential (i.e., stochastic) seismic events, based on a probabilistic seismic hazard assessment, that produce ground motion at the NPP site. These ground motions will be used to calculate probabilities of SSC failures at the NPP and levy. Based on probabilistic models of the conditional failure of piping systems and the flood protection levy, advanced flooding analysis will be run in locations of interest.

2.3 Role of the External Hazards Experimental Group in Risk-Informed Safety Margin Characterization Toolkit Development

Oberkampf and Trucano (2008) states that verification is "…the process of determining that a model implementation accurately represents the developer's conceptual description of the model and the solution to the mode" and validation is "the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model." An important R&D element of the RISMC Toolkit is the verification and validation of the advanced external hazard (seismic and flood) analysis tools developed. These tools, and their associated methods, are intended to provide best-estimates of both hazard probabilities and nuclear facility response under a range of hazard inputs in order to gain accurate risk insights and better ensure nuclear power plant safety during and after beyond design basis events. The computer codes must be able to accurately predict the response of NPPs during earthquakes, as well as the flow of water during flooding. The numerical tools will have mathematical equations that describe physics behavior, such as seismic wave propagation and water flow over complex geometry. Tools that will require validation include nonlinear time domain seismic analysis, such as MASTODON, which is under development in the MOOSE framework, and smooth particle hydrodynamic (SPH) analysis codes, such as NEUTRINO, the flooding simulation tool.

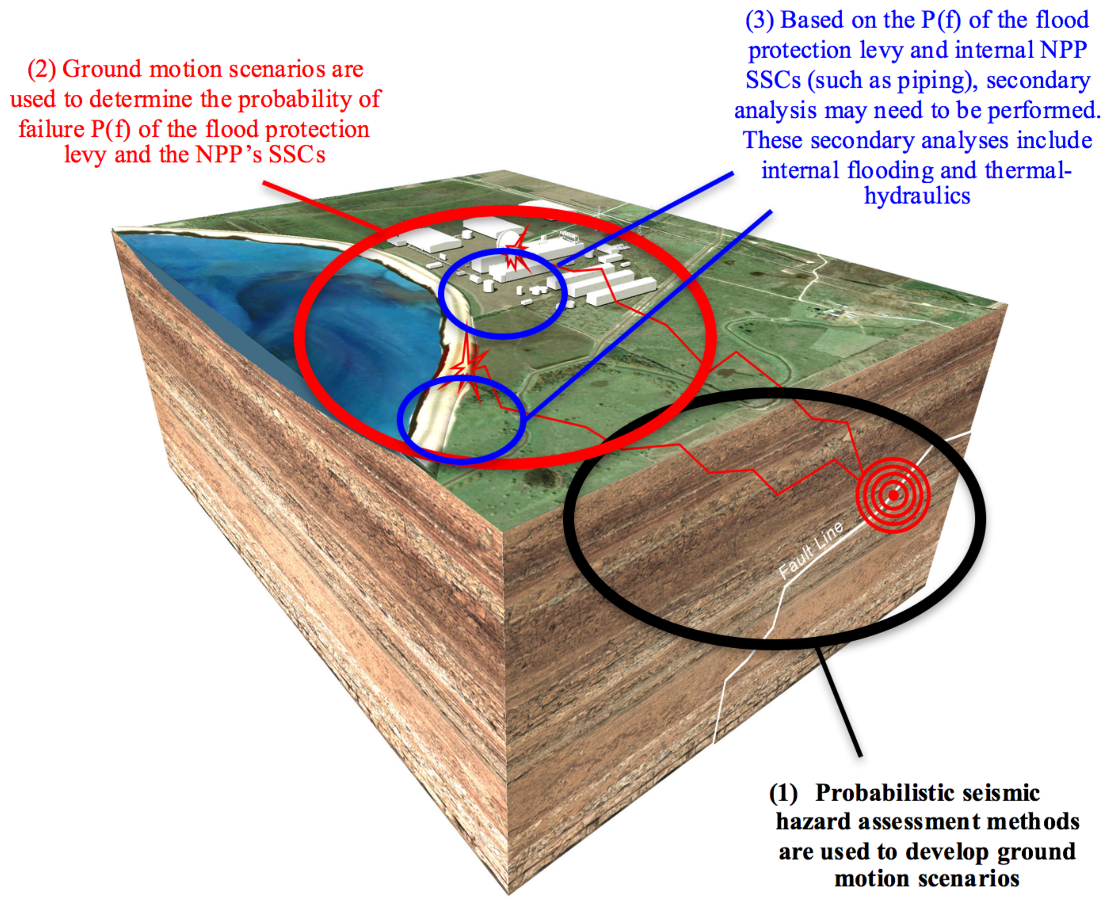

Figure 3. Multi-hazard problem solved using RISMC computational framework

It is important, in assessing and improving the tools developed, to identify the individual physics-based parameters that contribute the predictive capability of the tool. Each physical parameter can be validated starting at the element or unit level (i.e. the level at which an element has uniform properties and is under uniform loads) and the numerical capability improved. The next step is to validate tools and model performance at a benchmark tier (or tiers) with a slightly more complex experiment. Finally, system-level tests can be performed to validate the numerical code's predictive capability. Figure 4 lays out this process for developing and validating the predictive capability in numerical tools intended to perform site response and nonlinear SSI seismic analysis.

Currently, there is very limited data available to perform validation of the tools and methods being developed in the RISMC Toolkit. The EHEG is being developed to obtain high quality, large-scale experimental data validation of RISMC tools and methods in a timely and cost-effective way. The group of universities and national laboratories that will eventually form the EHEG (which is ultimately expected to include both the initial participants and other universities and national laboratories that have been identified) have the expertise and experimental capabilities needed to both obtain and compile existing data archives and perform additional seismic and flooding experiments. The resulting databases to be developed will be used to validate the advanced external hazard tools and methods.

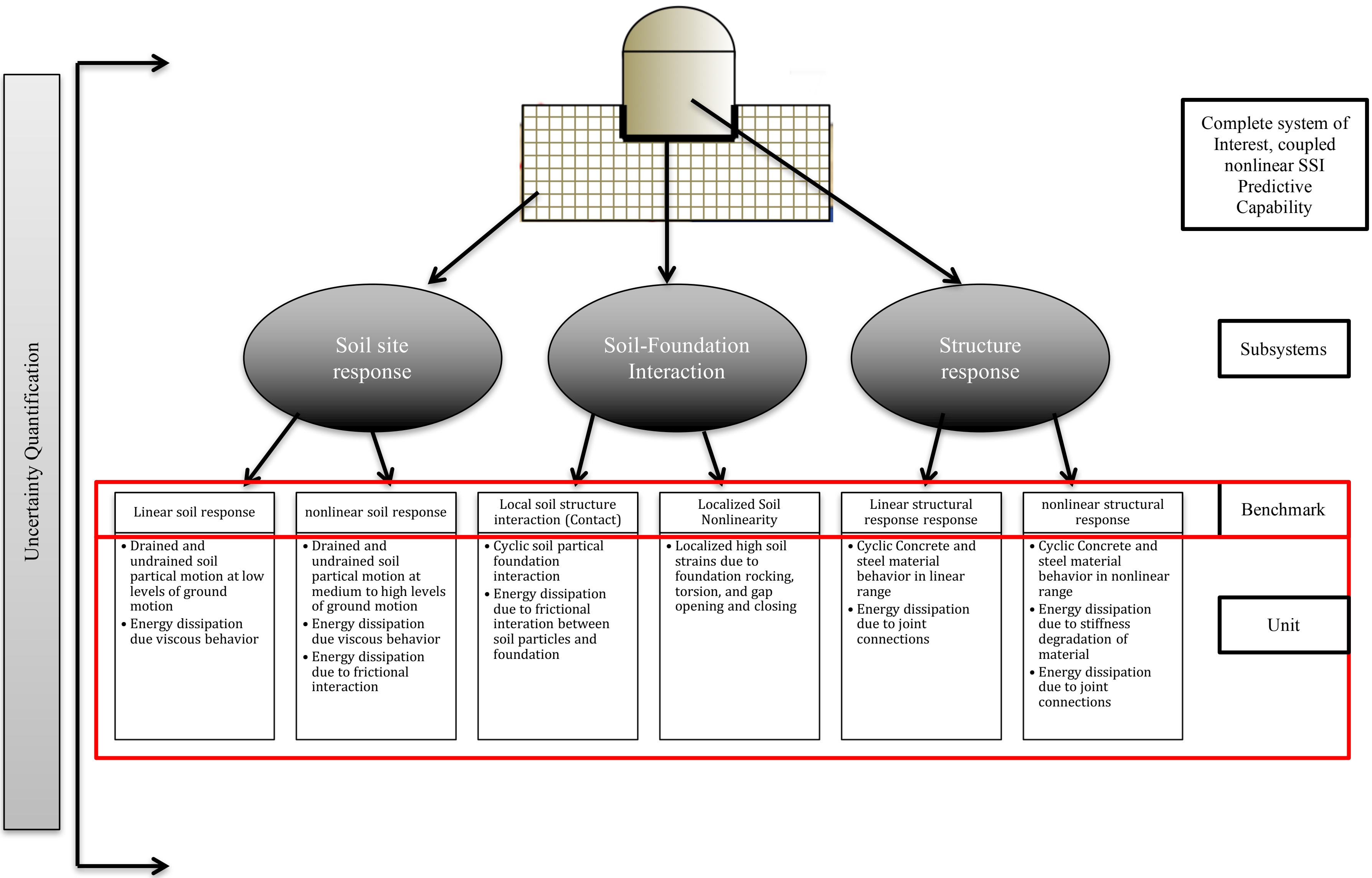

Figure 4. Validation process for developing a predictive capability of site response and SSI numerical tools

3. EXTERNAL HAZARDS EXPERIMENTAL GROUP CAPABILITIES AND STRUCTURE

3.1 Capabilities of the External Hazards Experimental Group

The EHEG will consist of experimental and human resources at the participating institutions. The EHEG will include recognized experts in the fields of seismic and flooding hazard assessment, site response analysis, and soil-structure-interaction (SSI) analysis. These experts will initially be drawn from INL, the University of Buffalo, Purdue University, University of Illinois, North Carolina State University, Idaho State University, and George Washington University. The intellectual and physical capabilities of these institutions that can be leveraged to provide services to perform experimental tests. A detailed table of the capabilities of each EHEG partner is provided in Appendix A.

3.2 Organization of the External Hazards Experimental Group

Representatives from these organizations will work together to form an EHEG Advisory Panel that will:

1. Develop a charter for the EHEG and establish ground rules for assigning experimental and research activities needed to meet customer objectives.
2. Recommend strategies for fulfilling high priority experimental needs identified by national laboratory, university, and industry customers.
3. Identify organizations that have the necessary equipment and qualified personnel to perform experimental work identified by customers.
4. Oversee the development of experiment teams that will be responsible for developing and executing detailed work plans that address experimental activities that are funded by the customers.

Specific activities that will performed by the EHEG advisory panel include the following:

- Each member organization will provide a principle investigator who will serve as a member of the EHEG Advisory Panel. The panel will evaluate seismic and flooding experiment requests that are received and make recommendations about institutions that are best suited to complete the experimental work. The principle investigator will be responsible for attending face-to-face meetings per year at the INL, or other advisory panel member facilities, and participating in conference calls where external hazard experimental proposals will be discussed and experimental work plans developed by working group members will be reviewed. The principle investigator will also be responsible for developing and submitting short reports that discuss the principle investigator's recommendations on how to best manage external hazard experimental work that is considered by the advisory panel.
- Each member organization will provide personnel who will participate in planning the proposed scope, schedule, and budget for external hazard experimental work that the EHEG Advisory Panel recommends be completed at the member's institution. The exact number of experiment planning activities that will be completed each year by each member organization will be dependent on the number of customers that approach the EHEG and on the Advisory Panel's recommendations. The work plans will provide all necessary details about the type of experimental work that will be performed, the number and qualifications of personnel who will complete the experimental work, the type and cost of new equipment that will be needed to complete the experimental work, the schedule for completing the experimental work, and the total cost for completing the experimental work. The member's principle investigator will also be responsible for presenting the experimental work plans to the EHEG Advisory Panel and working with the advisory panel to address requests for additional information.
- The EHEG Advisory Panel will work with external hazard experiment customers to resolve any issues associated with the proposed work that the customer identifies, establish contracts and other

documentation (e.g., non-disclosure agreements, export controls, software and hardware licenses, etc.) that cover the assigned work, and help the performing organization ensure experimental results are appropriately archived and communicated to the customer and the scientific community.

The EHEG activities will be managed through subcontracts established by INL, and INL will provide logistical support to the EHEG Advisory Panel to help enable successful completion of EHEG activities.

4. NEAR-TERM EXPERIMENTAL TEST PROGRAMS

There are several near term tests already planned and actively underway to gather data to validate both seismic and flooding models.

4.1 Seismic Testing

Adequate validation of site-response and SSI methods requires either field tests or large-scale experimental models, both of which are challenging to perform. The Seismic Research Group at INL will be performing a validation study for one-dimensional site-response analysis codes. The large-scale geotechnical laminar box at the University at Buffalo, shown in Figure 5, will be used for experiments designed to provide the appropriate large-scale test data. Once performed, this will be the first large-scale laboratory-controlled study available for validation of site-response analysis tools. Tests are scheduled to be performed in the summer of 2016.

Figure 5. Large-scale laminar box at the University of Buffalo

Gapping and sliding can significantly affect SSC response in nuclear structures, but these phenomena are currently not well understood. The Seismic Research Group at INL will be conducting experiments to provide (1) insight into the physics of gapping and sliding between soil and concrete and (2) data that will be used to calibrate the soil-foundation contact models used in nonlinear SSI simulations. The proposed gapping and sliding experimental test setup is shown in Figure 6.

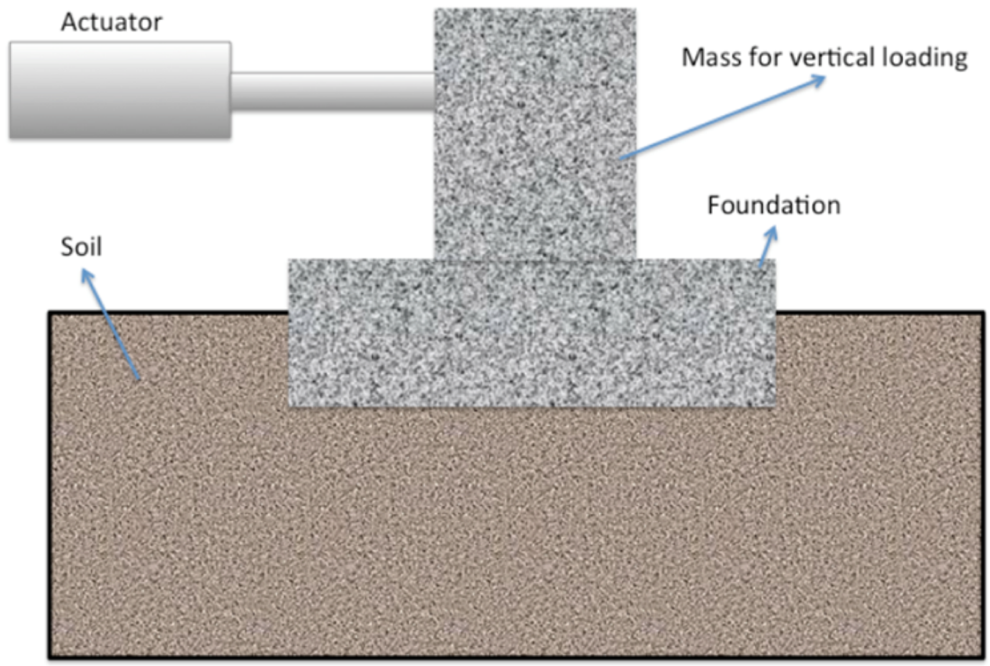

Figure 6. Proposed gapping and sliding experimental test setup

4.2 Flooding Testing

Flood-related experimental capabilities for the RISMC pathway should include the ability to test a variety of full scale components to failure under water spray, water rise, and wave impact flooding events. For flooding tests, initial tests of simple components will be run and the complexity of the experiments increased over time to include more prototypic components. The first phase of the flood experimental program focuses on the initial application and includes modifications such as instrumentation specific to the needs of flooding data collection and expansion of an existing water reservoir. These modifications will allow tests for water rise and spray scenarios. The later phase of testing will focus on wave impact testing. While the first phase is underway, research is being conducted into wave impact event generation and simulation.

Programmatic testing-related research is also being conducted in parallel with the testing described above. The program strategy will be to begin with conducting a large number of simple tests using simple components utilizing existing or easy to procure components and testing infrastructure. The goal of these tests will be to develop a qualitative understanding of how different kinds of components such as structural, mechanical, and electrical components behave in various flooding scenarios. As the testing capability increases, the testing methodology and sophistication will increase, building on the experience and insights gained in early testing. Testing with actual NPP components will carry certain higher costs and the testing protocol must be highly refined prior to conducting these tests to ensure the quality of the data is sufficient for use in assessing NPP risks. The program will solicit participation from industry and regulatory stakeholders and procure more complicated and prototypic NPP components. Figure 7, showing damage from the Fukushima Tsunami event in Japan, provides an example of the damage states of in-situ systems and components that the testing is intended to better understand and quantify.

Figure 7. Flooding damaged doorway example

After the qualitative understanding of component failure is developed in the early stages, fragility curves can begin to be developed that quantitatively describe the failure. A key part of this task is to identify the flooding variable which drives the failure and ought to be distributed in the fragility curve. Depending on the component and nature of the flood event of interest, water height may not always be the strongest variable to consider. Research should be conducted looking at how other factors play a role in failure. Other variables that may be important factors are the hydrodynamic (impulse) loading, time of submergence, scour, debris impact, or other factors. Determining when a component can resume its function after the water has receded may also be an important factor to consider. Once the fragility curves for critical components in the NPP have been developed they can be used to help inform plant stakeholders about the risk posture of the plant to various flooding scenarios. In order to be of use however, this data will need to be tied in with the codes in the RISMC Toolbox (as well as potentially new codes) to model risk informed safety margin.

An effort is also currently underway to test full scale doors using an existing water reservoir. For later tests, it is proposed to use a new larger setup. Flood testing will take on a variety of different forms. The water rise rates in the tank are likely to be a critical variable in understanding how the components fail. For the spray testing and later wave impact testing, large volumes of high velocity water coming from a bank of pressurized nozzles will impact the sides of the flooding chamber.

Additional testing will be conducted to assess the ability to simulate the hydraulic loads from high velocity waves using new approaches. Most open channel wave impact machines utilize a ram and even large facilities are only capable of simulating waves in the 5 foot range. An effort is underway using numerical models to determine if water transients can be developed in a *closed* channel system that simulates the hydrodynamic loading of a 10 foot by 10 foot section of a 20 foot tsunami wave. The effort is currently using a computational fluid dynamics code to map pressure forces to rigid bodies interacting with waves. One closed conduit concept being evaluated is depicted in Figure 8 and involves the rapid introduction of a large item (grey in color) to a reservoir that would generate the impulse necessary for the wave simulation.

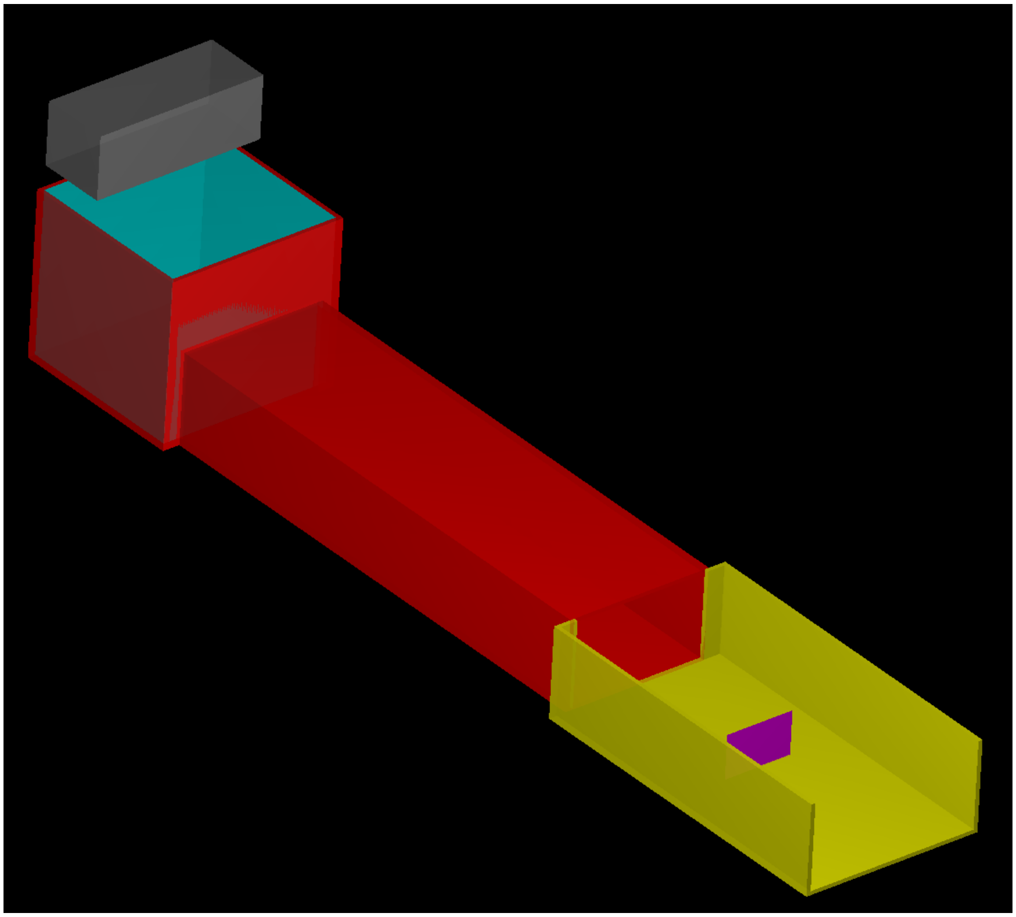

Figure 8. Closed conduit wave generation concept

Numerical simulation results will be compiled and used as the input to the design effort of the wave generation machine in Figure 8. A small scale prototype of this machine will be built and tested to verify its functionality. In more advanced tests, the wave impact machine will supply a short duration, high pressure slug of water, which will be capable of failing a component. An instrumentation and control system for this machine will be required as it will be desirable to monitor and vary the conditions of the wave impact tests.

5. SUMMARY

This report describes the development plan for a new multi-partner EHEG coordinated by INL within the RISMC technical pathway of the Light Water Reactor Sustainability Program. Currently, there is limited data available for development and validation of the tools and methods being developed in the RISMC Toolkit. The EHEG is being developed to obtain high quality, small- and large-scale experimental data validation of RISMC tools and methods in a timely and cost-effective way. The group of universities and national laboratories that will eventually form the EHEG (which is ultimately expected to include both the initial participants and other universities and national laboratories that have been identified) have the expertise and experimental capabilities needed to both obtain and compile existing data archives and perform additional seismic and flooding experiments. The data developed by EHEG will be stored in databases for use within RISMC. These databases will be used to validate the advanced external hazard tools and methods.

6. REFERENCES

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APPENDIX A – Intellectual and Physical Capabilities of EHEG Partners

Partner	Existing/ Future Capabilities	Capabilities	Description
Intellectual			
INL	Existing	Nonlinear seismic soil structure interaction method development	Using commercial time-domain codes to run sensitivity seismic sensitivity studies to further NLSSI R&D activities
	Existing	MASTODON	MASTODON will have the capability to perform stochastic nonlinear soil-structure interaction (NLSSI) in a risk framework coupled with virtual nuclear power plants (NPP). These NLSSI simulations will include structural dynamics, time integration, dynamic porous media flow, hysteretic nonlinear soil constitutive models (elasticity, yield functions, plastic flow directions, and hardening softening laws), hysteretic nonlinear structural constitutive models, and geometric nonlinearities at the foundation (gapping and sliding).
	Existing	Advanced seismic probabilistic risk assessment (SPRA) methods development	Developing a method for evaluating multi-hazard risk including seismic and flooding
	Existing	Time-based stochastic analysis	
	Future	Virtual external hazards at virtual reactors	Evaluate the risk of multiple hazards impact virtual nuclear power plants including all applicable physics to model the nuclear core response to those hazards.
University at Buffalo	Existing	Numerical analysis of seismic isolation systems	Significant experience with both testing and analysis of seismic isolation components and systems. Under NRC funding, developed isolator unit elements for multiple NLSSI codes.
	Existing	Advanced SPRA methods development	Developed new techniques for SPRA approaches for isolator and umbilical systems in isolated facilities.
	Existing	Nonlinear seismic soil-structure interaction analysis	Extensive experience with NLSSI analysis. With INL staff, authored non-mandatory appendix on NLSSI for ASCE 4-16.
George Washington University	Existing	Diagnostics development for time based analysis and code validation	Experimentalist team that has track record of developing custom diagnostics that are deployed on earthquake shake table. Extensive experience in computer model benchmark and validation.
Purdue University	Existing	Nonlinear seismic soil-structure interaction analysis	Capability to perform NLSSI evaluations
University of Illinois at Urbana-	Existing	Nonlinear seismic soil-structure interaction; Soil constitutive modeling;	Developed widely used numerical code for performing fully non-linear site response analyses. Under NRC funding, developing new soil constitutive model for

Partner	Existing/ Future Capabilities	Capabilities	Description
Intellectual			
Champaign		Discrete element modeling; Visualization	implementation in NLSSI codes.
North Carolina State University	Existing	Multi-hazard risk assessment	Seismically induced internal flooding due to leakages in pipes and tanks. Evaluation of piping vulnerabilities and integration with thermal hydraulic PRA for severe accident management particularly for beyond design basis events. Simulation of coastal storm surge flooding and storm wind effects for multi hazard PRA. Identification of previously unidentified critical paths due to correlated external/internal hazards. Consideration of Bayesian networks.
	Existing	Vulnerability assessment for SSC	Integration of component and subsystem level experimental data into system-level models for simulation of seismic performance of building-equipment-piping systems to include the effects of interactions among them. Uncertainty quantification in constitutive models for reinforced concrete and for steel. Propagation of uncertainty through system level simulations.
	Existing	Fragilities of flood defense structures	Uncertainty quantification and assessment of fragility surfaces for concrete protection structures such as walls, weirs, dams, and levees subjected to flooding and seismic loads. Consideration of structural as well as foundation failures.
	Existing	Equipment qualification	Reconciliation of experimental and simulation results for electrical cabinets and control panels. Characterization of uncertainty in mounting arrangement. Effect of high frequency ground motions on amplifications in the electrical cabinets and control panels.
Idaho State University	Existing	Flood/tsunami numerical modeling	SPH fluid modeling experience. Research into modeling of hydraulic structures and flood control structures.

Partner	Existing/ Future Capabilities	Capabilities	Description
Physical			
INL	Existing	Geotechnical centrifuge	Could be used to perform small scale soil experiments. Some modifications are necessary to a 1D shake table.
	Future	Small scale structural dynamics lab	Used to perform small scale structural dynamics experiments. The main goal is to allow INL researchers developing numerical code to also get experience in a physical environment and gather data used to frame larger scale experiments.
University at Buffalo	Existing	Two high-performance, 6 DOF shake tables	Tables can be relocated to adjacent positions or placed up to 92 feet apart (center-to-center). Together, the tables can support specimens of up to 100 metric tons and as long as 115 feet. When operated together, the tables can be programmed with identical or uncorrelated dynamic motions. Each shake-table surface has plan dimensions of 12 ft. x 12 ft. Two 23 ft. x 23 ft. shake-table extension platforms are available for both shake-tables. Use of the table extensions extends the footprint available for test specimens.
	Existing	Nonstructural Component Simulator (NCS)	The NCS is a modular two-level testing frame for experimental performance evaluation of nonstructural components and equipment under realistic full scale floor motions. The NCS can provide the dynamic stroke necessary to replicate full-scale displacements, velocities and accelerations in the upper levels of multi-story buildings during severe earthquake shaking. The system can test nonstructural components and equipment at up to 3 g horizontal accelerations with specimen capacity of up to 6.9 kips per level. Vertical accelerations can also be included in an experiment by mounting the NCS on one of the shake-tables.
	Existing	Large-scale geotechnical laminar box	Designed for soil-foundation-structure interaction studies near full scale. The laminar box comprises 39 rings or laminates built of welded I-beams, stacked vertically to form a rectangular box. Each laminate is supported by ball bearings that are fixed to the laminate below. The laminates are separated by a 0.2 in. gap. The stacked laminates are mounted on a sliding steel base assembly that is supported by 288 ball bearings. The sliding base is installed on a steel plate that is bolted to the strong floor. Two 110-kip dynamic actuators are connected between dedicated reaction blocks and the sliding base. When subjected to periodic or simulated seismic motions, the laminar box and the soil contained within deform in a manner

Partner	Existing/ Future Capabilities	Capabilities	Description
Physical			
			that simulates free ground response. The laminar box has a maximum height of 19.7 ft. The nominal internal dimensions are 16 ft. long x 9 ft. wide. The enclosed volume can be filled with a saturated sand or soil to a maximum capacity of 100 cubic yards, using a hydraulic slurry pump and distribution system. A supply of Ottawa (F-55) sand is stored in three (65.4 cubic yards each) outdoor storage containers and is available for use in sponsored projects. Use of other soil materials is possible.
	Existing	Hybrid simulation systems	Two hybrid simulation systems are available, both of which are connected via SCRAMNet shared-RAM access to the shake-table and structural test controllers, data acquisition systems, and dedicated real-time control computer hardware. The hybrid platforms can be deployed on experiments using the east shake-table, the NCS or any of the structural actuators. The hybrid simulation platforms are typically programmed using MathWorks MatLab and Simulink, for which SEESL has licensing and maintenance agreements.
George Washington University	Existing	Modal and tensile testers	Modal Teste: Vibration Research system. 0-3,000 Hz, 80 lbf Tensile Tester: 10,000 lbf
	Existing	Dedicated high-bay space with strong floor	25' ceiling, 1,340 sqft, 26'x10' strong floor, 1 MW of electrical power, 4 tons crane, 75 Hp Hydraulic Pump
	Existing	Large, polyvalent, and transportable suite of advanced diagnostics proven on shake table	27 cameras total, including cameras able of exposure down to 10 ns and single photon detection, speed of 1.3×10^6 frames/second, recording time of several hours; light sources ranging from lasers (0-100 kHz from UV to IR), strobe LEDs (0-100 kHz), Flood lights, etc; in-house and commercial Digital image correlation, particle image velocimetry codes
	Future	1D 10'x10' shake table	MTS , 0-50 Hz, 6 Mtons
	Future	1D 5'x5' shake table	MTS, 0-100 Hz, 1 Mtons
University of Illinois at Urbana-Champaign	Existing	Illinois Multi-Directional Cyclic Simple Shear Device for soil testing.	Multi-directional simple shear device capable of performing both drained and fully saturated testing on element-level specimens of sand and clay materials. Most appropriate testing methods for development of soil constitutive models.
	Existing	Monotonic and cyclic triaxial soil testing	Testing device used for consolidation and strength testing of geotechnical materials.

Partner	Existing/ Future Capabilities	Capabilities	Description
Physical			
	Existing	Resonant column soil testing	Testing device appropriate for determination of appropriate V_S and G_O properties of geotechnical materials to be used in site response and SSI analyses
Purdue		Wykeham Farrance unsaturated dynamic hollow cylinder device capable of testing hollow or solid specimens	Testing device appropriate for determination of appropriate V_S and G_O properties for unsaturated soil materials to be used in site response and SSI analyses
		Automated triaxial testing (CKC) system for cyclic or monotonic loading with user-defined stress paths, equipped with bender elements	Testing device capable of determining V_S and G_O properties of geotechnical materials. Also, commonly used for consolidation and strength testing of geotechnical materials.
		Automated MTS programmable load frame for stress- or strain-controlled dynamic or monotonic testing, allowing testing of geotextiles, and independent control of pore water pressure or confining stresses	Testing device capable of determining properties of geotextiles and other laminar materials. Of use for testing materials used to represent vapor barrios in gapping and sliding testing.
		Small- and large-scale direct shear boxes, ring shear device and pull-out box	Testing device used for strength testing of geotechnical materials. Capable of assessing crushing of particulate materials under load.
		Hydraulic static and cyclic actuators with up to 1000 kip capacity	Can perform dynamic soil-foundation interaction analysis
Idaho State University	Existing	Water flume and associated water storage/pumping	Used to develop flooding fragilities of SSCs